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BONE BEDS AT THE BOUNDARY: ARE THEY A REALISTIC EXPECTATION? A. H. Cutler and A. K. Behrensmeyer, Department of Paleobiology, NHB MRC-121, Smithsonian Institution, Washington DC 20560, USA.

Over the past decade and a half an impressive array of evidence has been amassed to support the hypothesis that the Mesozoic Era was brought to a close by the impact of one or more extraterrestrial bodies on the Earth [1–3]. The most convincing lines of evidence have been mineralogic, geologic, and geochemical rather than paleontologic. Indeed, the fossil record remains ambiguous, and paleontologists disagree as to whether the putative impact was in fact responsible for abrupt and widespread extinction of species [4]. The problem is especially acute for the terrestrial record where KT boundary sections are not extensive and the fossil record tends to be fragmentary and facies-dependent [5].

One source of confusion is the absence of a clear picture of what the fossil record of a global catastrophe should look like. Signor and Lipps [6] made an early contribution along these lines by pointing out that the vagaries of preservation would tend to truncate species' apparent ranges below their true level of extinction, with the result that truly abrupt extinction events would appear gradual in the fossil record. In their analysis, however, Signor and Lipps assumed that taphonomic processes remained constant up to and across the extinction boundary, and at least one author [7] has suggested that the scale of mortality implied by an impact should be reflected in the record by widespread bone beds and mass mortality horizons.

Mass mortality horizons associated with local or regional events such as droughts [8], fires [9], and volcanic ashfalls [10] can be documented in the vertebrate fossil record. Is it reasonable to expect that mass mortality of large vertebrates on a global scale would leave a recognizable signal in the record? It is obviously too much to expect to find vast horizons of dinosaur carcasses in their final death postures dusted with a layer of Ir, but it is less obvious whether such an event would produce a detectable elevation in the frequency or scale of bone concentrations (a "bone spike") at the extinction horizon.

Based on calculations of mortality (turnover) rates of dinosaurs from known relationships of body size to life span [11, 12], estimates of the dinosaur-carrying capacity of the late Cretaceous ecosystems (animals/km²) and faunal lists indicating the number of coexisting species of animals >20 kg [13] we infer a range of probable densities of live animals and carcasses on the landscape of the latest Cretaceous. From this we infer the differences between a bone assemblage formed under normal turnover (attritional input of bones) and from a catastrophe that wiped out all large tetrapods over a period of hours to days. In addition to the issue of attritional vs. single-pulse

availability of carcasses, longer-term effects of burial and preservation of bone-bearing strata must be taken into account in assessing whether a mass die-off of dinosaurs would leave a detectable signal in the fossil record at the KT Boundary. We conclude that it is unlikely that a single event such as a bolide impact would leave dense, multispecies dinosaur bone beds in the area of greatest mass mortality.

It is possible that ecological stress farther from the impact site, which allowed some species time to congregate around specific areas prior to death (waterholes, remaining patches of forage), would have created more concentrated bone assemblages for particular taxa. Whether any of these were preserved in the long run would depend on whether such zones of variable, "less catastrophic" mortality intersected active areas of deposition at the time. Recovery of a fossil record from these same areas would depend also on later tectonic processes that created outcrops, which we can search today. The complexity of the combined requirements for there to be a record of any major mass mortality event for land animals at the KT boundary makes it unlikely that this will be detectable. The absence of bone beds at the boundary should not be used for or against hypotheses regarding causes of the extinction event.

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IMPACTS, EXTINCTIONS, VOLCANISM, GLACIATIONS, AND TECTONICS: MATCHES AND MISMATCHES. I. W. D. Dalziel, Institute for Geophysics, University of Texas, 8701 N. Mopac Expressway, Austin TX 78759-8397, USA.

The debate concerning possible relations between impacts, extinction events, and volcanism has recently taken a new turn. Diamictites and associated sedimentary deposits long regarded by geologists as glaciogenic, have been reinterpreted as impact-related. Going further, the Permo-Carboniferous diamictites that are widespread in the southern continents and India are now put forward as evidence that fragmentation of the Gondwana supercontinent in the Mesozoic was a direct result of meteorite impact. In an abstract at a meeting of the American Geophysical Union, and in an article in the popular press, one member of the earth science community has made a specific claim to identify the site of the supercontinent-destroying bolide on the Falkland/Malvinas Plateau. It is claimed by this scientist that the Cape fold belt in Africa represents a "breaking wave" of deformation resulting from this impact, and that fractures in the clasts of the Dwyka diamictite in southern Africa represent impact-induced cataclasis of the target rock. These hypotheses fly in the face of the well-established tectonic history of the Gondwana supercontinent in several respects.

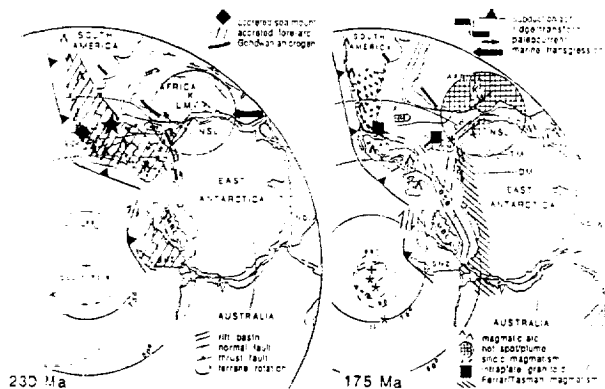


Fig. 1. (a) Gondwana during the Late Triassic (230 Ma) after the Gondwanide orogeny, based on the reconstruction of Grunow et al. (1991), intraplate deformation in Africa, after Daly et al. (1991), and reconstruction of the Gondwanide orogen, after Dalziel and Grunow (1991). Arc magmatism from Pankhurst (1990). The positioning of the incipient Karoo/Bouvet plume (circle) follows that of White and McKenzie (1989). AP = Antarctic Peninsula block; EWM = Ellsworth-Whitmore Mountains block; FI = Falkland Islands terrane (shape schematic); K = Karoo Basin; LM = Lebombo monocline; MBL = Marie Byrd Land; NSL = Neuschwabenland; SNZ = south New Zealand (South Island, Campbell Plateau, and Chatham Rise); TI = Thurston Island block. Dashed circles are confidence circles about paleomagnetic poles (asterisks and crosses) of Grunow et al. (1992) and are identified by letters as above. Reconstructions are polar stereographic projections centered on the paleomagnetic South Pole (cross) determined for East Antarctica (eat). (b) Gondwana in the Middle Jurassic (175 Ma) after the rotation of the Falkland and Ellsworth-Whitmore Mountains blocks, based on the reconstruction of Grunow et al. (1991). The location of the magmatic provinces follows Cox (1978), Dalziel et al. (1987), White and McKenzie (1989), and Storey and Alabaster (1991). Additional abbreviations: BSB = Byrd Subglacial Basin (including Bentley Subglacial Trough); DM = Dufek Massif; EW = Explora wedge; TM = Theron Mountains.

1. The suggested site of impact is the Lafonian (Falkland/Malvinas) microplate that was displaced relative to both South America and Africa after the time of the proposed impact and before opening of the South Atlantic Ocean basin. Hence the suggested geometric relationship of this site to surrounding features such as the Cape Fold Belt is incorrect (see Fig. 1).

2. Gondwana reconstructions based on sea-floor spreading and paleomagnetic data show that the Gondwanide fold belt is almost rectilinear from Argentina, through southern Africa, to the Pensacola Mountains of Antarctica. It is not circular in plan view (see Fig. 1).

3. The Gondwana diamictites and associated deposits are diachronous and track the paleomagnetically determined position of the South Pole across the supercontinent in the Devonian, Carboniferous, and Permian.

4. Gondwanide deformation is also diachronous: Even within the Cape fold belt it extended from ca. 278–230 Ma. It took place behind an active subducting margin of the Pacific Ocean.

5. The fracturing of the clasts in the diamictites can be directly related to strain during a mid-to-Late Permian or Triassic phase of deformation in the Gondwanide fold belt. Glossopteris-bearing Permian strata overlie the diamictites everywhere, and were deformed with them during the Gondwanide folding.

Leaving aside the issue of obvious distinctions (textural, metamorphic, etc.) between modern tillites and deposits such as the

Onaping Formation of the Sudbury basin that are widely accepted as being impact related, it is unfortunate that the largest extinction event in Earth history should have been related in such a cavalier fashion to geologic features spanning several tens of millions of years (indeed even hundreds of millions of years to judge by maps shown at AGU and published, with attribution, in the popular press). Geologists clearly need to consider impact of extraterrestrial bodies as a major agent of tectonic as well as environmental change. But as students of impact and its effect on our planet reach back in time from the KT boundary, it is all the more important for them to look carefully at its complex tectonic history in relation to the geologically instantaneous events that they invoke.

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SULFATE VOLATILIZATION, SURFACE-WATER ACIDIFICATION, AND EXTINCTION AT THE KT BOUNDARY.

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It appears that the severity of environmental effects related to the KT boundary impact may have been largely due to the unusual geochemistry of an evaporite-rich impacted terrane. KT tektite composition, experimental results, and comparison to Yucatan stratigraphy all indicate the presence of gypsum or anhydrite at the tektite source (Chicxulub crater). Thick (~1-km) Late Cretaceous evaporite sequences occur in the region of the Chicxulub KT impact structure [1]. Calcium-rich KT tektites contain high SO_3 concentrations (0.83% [2]; 0.53% [3]; range = 0.20–1.0%). They also exhibit $\delta^{34}\text{S}$ values typical of evaporites (13.2‰ [2,4]). Experimental results have duplicated the high-Ca tektite composition by high-temperature melting of evaporite + andesite [2,5].

Several studies have estimated the amount of SO_2 volatilized from target evaporites by the KT impact. An estimate of 1.3×10^{16} was based on the proportion of unaltered high-Ca glass in Haiti and the global thickness of the KT boundary clay. This assumed that 1000 km^3 of impact glass was created and 2% was high-S glass derived from evaporite source [2,5]. This represents a minimum estimate, since it is limited to SO_2 released by tektite formation and does not include SO_2 released from solid rock by shock, or SO_2 released by initial volatilization of the target. More comprehensive estimates have been derived from reconstruction of Chicxulub geology and assumed shock pressures required for sulfate release. These rely on variable estimates of transient crater diameter (80 to 146 km), stratigraphy of Chicxulub region (0.5 to 1.5 km anhydrite), and shock pressure of sulfate release (20 to 40 GPa). Based on such criteria, Sigurdsson et al. [5] estimated that 2.4×10^{18} to $8.4 \times 10^{18} \text{ g}$ SO_2 was released, Brett [6] estimated that $4 \times 10^{17} \text{ g}$ SO_2 was released, and Pope et al. [7] estimated that 5.4×10^{17} to $1.6 \times 10^{18} \text{ g}$ SO_2 was released.

Combined with the great optical depth loading previously estimated to result from the KT impact "dust" cloud, the resultant stratospheric S aerosols may have contributed to a rapid decline in global surface temperatures to near-freezing in about one week [5]. Time-dependent conversion of stratospheric SO_2 to H_2SO_4 would have prolonged this cooling for several years [5]. These stratospheric sulfate aerosols may also have caused global "blackout," preventing photosynthesis for months and disrupting it for years [7]. These relatively long-lived effects of the estimated SO_2 release